An Analytical Method to Parameter Estimation by Dynamic Performance Evaluation

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Abstract

An analytical method of parameter estimation for the synchronous generator based on dynamic behavior evaluation is proposed in this paper. For this purpose, based on the concept of performance deviation of generator with respect to change of parameters, this paper proposes a deviation index showing the effect of change in each parameter on output variables of generator such as active, reactive and apparent powers, rotor angle, terminal voltage and armature current. In other words, the bigger value of deviation index for an output variable with respect to a specific parameter shows better estimation of parameter from that output variable. In fact, the deviation index represents estimation of each parameter within the change in dynamic behavior of generator. The proposed concept and approach is demonstrated on a test system with 25 buses and 12 machines test system.

Keywords

Synchronous Generator; Parameter Estimation; Dynamic Performance; Output Variables

Introduction

Synchronous generator modeling is a very important part of power system modeling and simulation. It plays a vital role in assessing dynamic security of power systems. Proper representation of synchronous machines based on accurate adoption of parameters is necessary for valid dynamic simulation studies. Development of Park's model was a well known and a outstanding achievement in the modeling synchronous generator for dynamic studies (Park, 1929). The detailed modeling provides proper information for steady state and dynamic operation of synchronous machines. It is a standard practice in power engineering to utilize Park's model for modeling synchronous generator in all power system applications. For modeling of synchronous generator, parameter identification is a challenging problem attracting attention of many researchers. Accurate identification of generator parameters is necessary for performing stability studies and post mortem analysis of power systems. Traditionally, synchronous machine parameters are evaluated by off-line tests. These methods assume a known structure for synchronous machine while using well-established theories like Park's transformation. Usually the procedures involve difficult and time-consuming tests, such as; short-circuit, standstill frequency response (SSFR) and open circuit frequency response (OCFR) tests (Dandeno, 1999, Escarela-Perez, 2001). These tests can be mainly carried out when the machine is not in service. The main problem with this approach, classified as white-box modeling, is that the parameters are determined individually using off-line tests. These are facing with errors when parameters are used collectively to simulate the behavior of synchronous generator. The errors may come from the fact that the assumed well known structures may not accurately model the machine at all operating conditions. To overcome these, different structures for synchronous machines compared to the traditional d-q axis model, have been proposed (Chan, 2001, Cui, 2004). Moreover, identification methods based on the on-line measurements have been proposed and gained attention during recent years (Melgoza, 2001, Kyriakides, 2004). However, in the on-line parameter identification the main question is which operating variables are the most suiTABLE operating data with enough information to be used for parameters extraction. In all methods developed for generator modeling and parameter identification, it is well understood that inaccuracy and errors appeared in the identified parameters can affect dynamic performance of generators which may affect system stability. This paper proposes an analytical method in identifying suiTABLE variables containing enough information to

estimate parameters of synchronous generators.

In this paper in order to find the most proper operating variables to be used for on-line parameters identification, the trend of change of parameters within generator dynamic behavior is investigated. In other words, by recognizing the most affected operating variables with respect to changes of a specific parameter, these variables are used as the most informative variables for on-line identification of that specific parameter. For this purpose, an estimation index is proposed which is evaluated based on the sensitivity of output variables of generator with respect to parameter changes. This index is used as a measure for estimation of parameters of generators. After introduction description of machine, model is presented. Then concept of estimation index is discussed followed by principle of the proposed approach. Simulation studies and summarized conclusions are presented in the last two sections.

Machine Model Description

Park's Model of Synchronous Machine

Fundamental equations of synchronous machine were derived by Park and others years ago. Park's equations have the simplest form and are the most well known. FIG. 1 shows Park's synchronous machine model. Three armature phases winding *a*, *b* and *c* on the stator of the machine have been replaced by two equivalent *d* and *q* armature windings located on the *d* and *q* axes respectively. There are two damper windings on the rotor, *D* on the *d*-axis and *Q* on the *q*-axis which are permanently short-circuited. There is also a field winding *F* on the *d*-axis, which is DC-excited. Assuming only one common mutual for all windings per axis, the flux linkages of the *d*- and *q*-axis windings of FIG. 1 may be expressed as follows:

$$\begin{bmatrix} \Psi_d \\ \Psi_F \\ \Psi_D \end{bmatrix} = \frac{1}{\omega_0} \begin{bmatrix} x_d & x_{md} & x_{md} \\ x_{md} & x_F & x_{md} \\ x_{md} & x_{md} & x_D \end{bmatrix} \begin{bmatrix} -i_d \\ i_F \\ i_D \end{bmatrix} \qquad (1)$$

$$\begin{bmatrix} \Psi_q \\ \Psi_Q \end{bmatrix} = \frac{1}{\omega_0} \begin{bmatrix} x_q & x_{mq} \\ x_{mq} & x_Q \end{bmatrix} \begin{bmatrix} -i_q \\ i_Q \end{bmatrix} \qquad (2)$$

In the development of synchronous machine model, parameters are usually treated as operational parameters. Such parameters include but not limited to synchronous reactance for steady-state analysis, transient and sub transient reactance including the effect of field winding and damper winding for transient and dynamic studies and the transient and sub transient time constants associated with corresponding reactance. TABLE 1 summarizes these parameters.

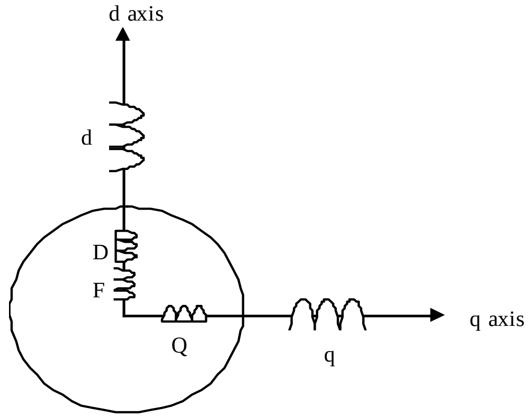

FIG. 1 PARK'S SYNCHRONOUS MACHINE

TABLE 1 SYNCHRONOUS GENERATOR OPERATIONAL PARAMETERS

Parameter	Description
X_d	Unsaturated d axis synchronous reactance
X'_d	Unsaturated d axis transient reactance
X''_d	Unsaturated d axis subtransient reactance
X_q	Unsaturated q axis synchronous reactance
X'_q	Unsaturated q axis transient reactance
X''_q	Unsaturated q axis subtransient reactance
T''_d	d axis subtransient short circuit time constant
T'_d	d axis transient short circuit time constant
T''_{do}	d axis subtransient open circuit time constant
T'_{do}	d axis transient open circuit time constant
T''_q	q axis subtransient short circuit time constant
T'_q	q axis transient short circuit time constant
T''_{qo}	q axis subtransient open circuit time constant
T'_{qo}	q axis transient open circuit time constant

Effect of Generator Parameters on System Stability

Synchronous generators play a dominating role in the dynamic performance of power systems. Load-angle stability of power systems is mainly affected by the performance of synchronous generators. Proper modeling of synchronous generators enables one to simulate dynamic behavior of synchronous generators and power systems in a realistic environment. The accuracy of generator modeling mainly depends upon the accuracy of generators parameters. Generator parameters are provided either by the manufacturers or by identification process. For the purpose of parameter identification so far many techniques and methodologies have been developed. Different values for generator parameters could result in different dynamic behavior for generators and power system. During dynamic behavior, generator parameters have a great effect on variation of machine output variables such as active and reactive powers, voltage and load angle. Variation in output variables of generator depends on the type of parameter such that different parameters may have different effect on the output variables. In other words, by changing a specific parameter and applying a disturbance, the most affected output variables of the generator due to the change in the parameter is chosen as the proper operating variables for identifying that parameter.

Estimation Index

As mentioned before, effect of generator parameters on its dynamic behavior and output variables differs from parameter to parameter. In fact manner of variation of each output variable of generator contains useful information regarding generator parameters. Therefore, the generator parameters could be extracted from the information concealed in the content of output variables of generator. For example rotor angle could be generally expressed as a function of generator parameters as follows:

$$\delta = f(T''_d, T'_d, T''_q, T'_q, H, X''_q, X'_q, X_q, X''_d, X'_d, X_d) \qquad (3)$$

Where, f is an implicit function expressing the relation between rotor angle and generator parameters. It is noteworthy that each output variable contains different information with respect to different parameters. Some parameters have more significant effect on output variables compared to other parameters and these parameters are more estimable from the information concealed in the content of those output variables. Therefore, estimation of each parameter from output variable is different. In this paper estimation of each generator parameter from dynamic behavior of output variables and also the possibility for extracting that parameter from those output variables are investigated. In this method, by changing each parameter and applying a fault, output variables of generator are calculated by time domain simulation. In order to evaluate the changeability of output variables with respect to change in a specific parameter, a deviation index based on the square error of each output variable between two cases, before and after the change in parameter, is calculated as follows.

$$DI_i^k = \frac{1}{n}\sqrt{\sum_{t=1}^{n}\left(Y_i^k(t) - Y_i^0(t)\right)^2} \qquad (4)$$

Where, $Y_i^0(t)$ is value of the i^{th} output variable at time step t corresponding to the base value of the parameter; $Y_i^k(t)$ is value of the i^{th} output variable at time step t corresponding to the k^{th} step change in the parameter; n is number of time steps and DI^k_i is deviation index associated with the i^{th} output variable with respect to the k^{th} step change in the parameter. Larger deviation index for an output variable is equivalent to being more informative with respect to parameter identification.

Proposed Approach

In this section, a method for identifying the most informative and relevant output variables needed for extracting each parameter of generator is proposed. In this method, by changing each parameter of generator and applying the process shown in Fig. 2 and calculating the DI index from equation (4) the most informative output variable is found.

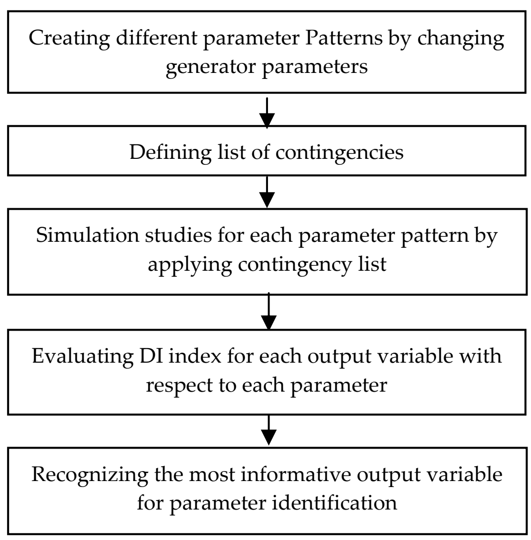

FIG. 2 PROCESS OF THE PROPOSED APPROACH

Firstly, different parameter patterns considering parameter changes are created. For this purpose each parameter is individually changed, increased or decreased around its base value through a number of steps. Therefore, each pattern consists of only one parameter but with different values including its base value. Notice that changes in a parameter are conducted while other parameters are kept constant. Then dynamic behaviour of synchronous generator with respect to each parameter pattern is evaluated using transient stability simulation for two types of disturbances, a fault at generator terminal and a step change in turbine output power as severe and medium disturbances respectively. The output variables of generator such as active and reactive power, terminal voltage, armature current and rotor angle are calculated with respect to step changes defined for each parameter and for applied disturbances. Finally, DI index as defined in (4) is calculated for each output variable and with respect to each parameter.

Simulation Results

In order to demonstrate effectiveness of the proposed approach, it is applied to a test system with 25 buses, 53 lines and 12 generators extracted from Iran HV power system as shown in FIG. 3. Simulation studies have been carried out using DigSILENT Power Factory 13.2 and MATLAB 7 software packages.

Simulation studies are carried out according to the steps defined in FIG. 2. The generator parameters considered in this investigation are as follows:

$$T''_d, T'_d, T''_q, T'_q, H, X''_q, X'_q, X_q, X''_d, X'_d, X_d \qquad (5)$$

The generator adopted for study is a generator with the base parameters shown in TABLE 2.

Two kinds of disturbances as follows are applied for actuating dynamic behavior of generators:

1) A three phase short circuit at the terminal of generator under study
2) A Step change in turbine output power of the generator under study

Active, reactive and apparent power, terminal voltage, armature current and rotor angle of the generator are considered as output variables for estimation analysis of generator dynamic behavior. By using transient stability simulation the output variables of the generators are evaluated for 10 seconds with the time interval 0.1 second. FIG. 4 and 5 show variation of reactive power and armature current respectively for the generator under study with respect to the change in X'_d through 10 steps while the disturbance is stepped change in turbine output power.

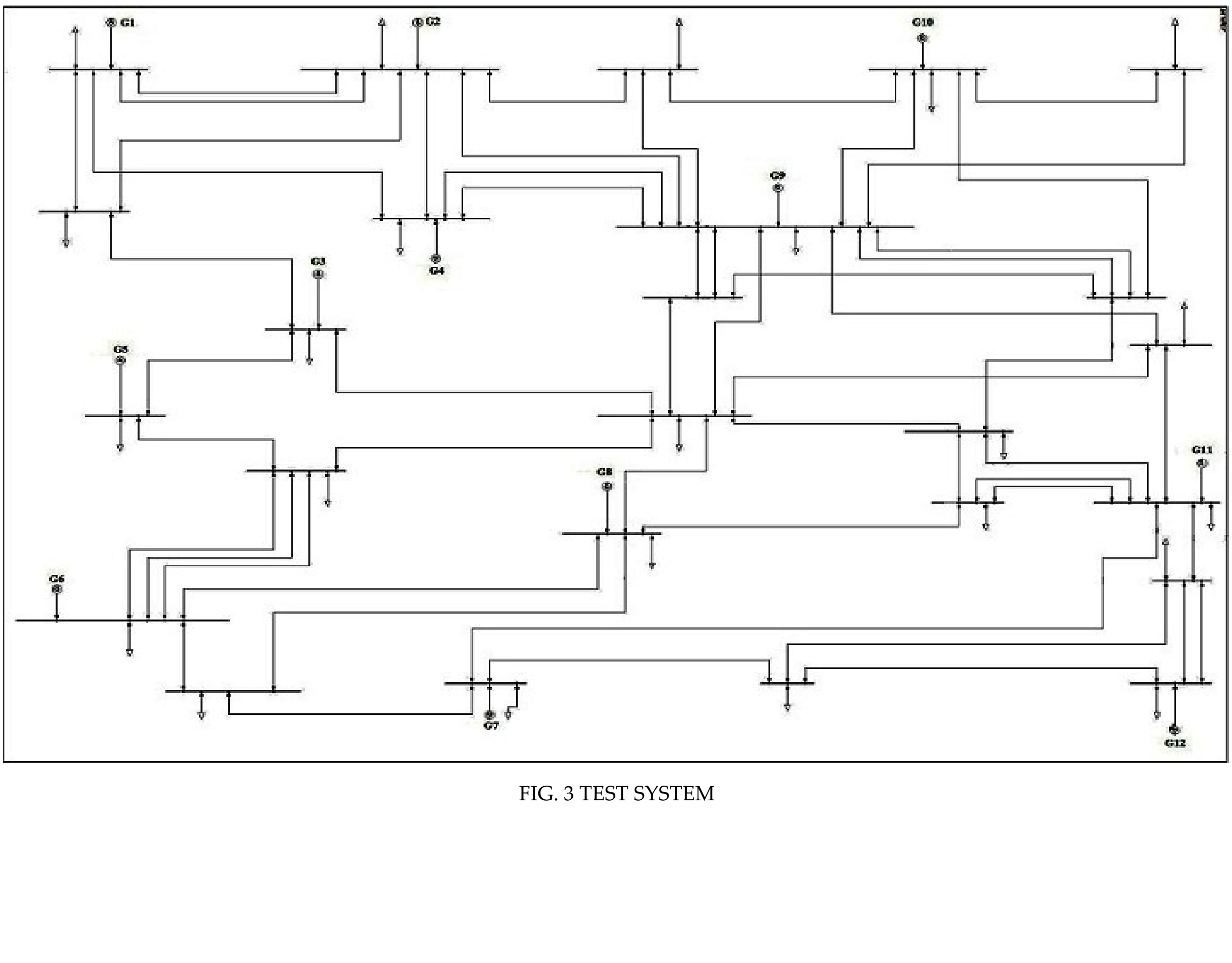

FIG. 3 TEST SYSTEM

As it can be seen from FIG. 4 and 5, dispersal in reactive power is more than armature current, which means that reactive power variation is more affected by the change in X'_d and consequently contains more information about X'_d. In order to evaluate the DI index for all output variables of generator with respect to all parameters, all eleven parameters shown in the TABLE 2 are changed individually by 10 steps and 110 (=10*11) parameter patterns are created. By applying two disturbances for each parameter pattern, totally 220 dynamic patterns are generated. Then, by dynamic simulation, 220 patterns for dynamic behavior are obtained.

TABLE 2 BASE VALUE OF PARAMETER OF GENERATOR UNDER STUDY

Parameter	Description
X_d (p.u)	2.07
X'_d (p.u)	0.328
X''_d (p.u)	0.245
X_q (p.u)	2.01
X'_q (p.u)	1.1
X''_q (p.u)	0.264
T'_d (p.u)	1.5
T''_d (p.u)	0.35
T'_q (p.u)	0.4
T''_q (p.u)	0.35
H (sec)	4.2

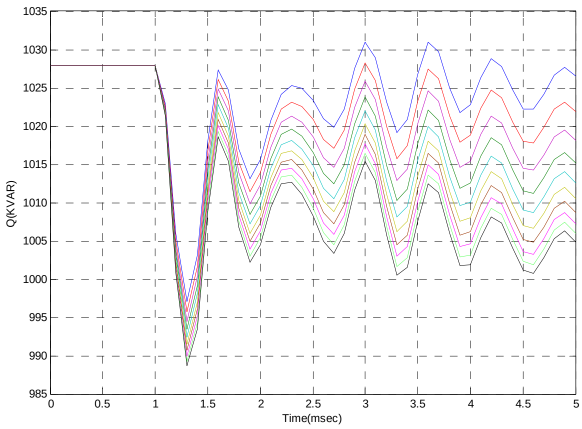

FIG. 4 VARIATION OF REACTIVE POWER OF GENERATOR UNDER STUDY WHEN X'_d IS CHANGED IN 10 STEPS AND FAULT IS A STEP CHANGE IN TURBINE POWER

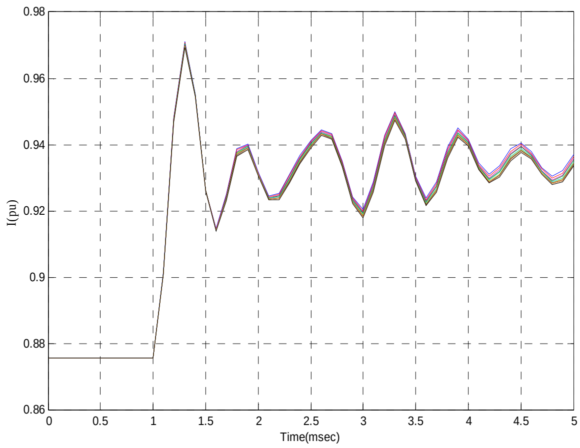

FIG. 5 VARIATION OF ARMATURE CURRENT OF GENERATOR UNDER STUDY WHEN X'_d IS CHANGED IN 10 STEPS AND FAULT IS A STEP CHANGE IN TURBINE POWER

In fact, with respect to a change in each generator parameter a corresponding change and variation can be obtained for all output variables. Regarding a step change in a specific parameter X_i, the difference of output variable V_i^k corresponding to that step change with the output variable V_i^0 corresponding to the base value of that parameter is used to evaluate corresponding deviation index DI_i^k using equation (4). FIG. 6 shows the variation of DI index for output variables with respect to change in inertia constant H of the generator under study when fault is applied at the generator terminal while FIG. 7 shows variation of DI index for output variables with respect to changes in X'_d when fault is step change in the turbine output power of the generator under study. As it can be seen from FIG. 6 and 7, variation of DI index for different output variables of generator are not the same. The value of DI variation for the active power with respect to parameter H and for reactive power with respect to parameter X'_d is bigger than the value of DI indices corresponding to other output variables. A higher value of DI index for an output variable V^k with respect to parameter X_i, means better estimation for parameter X_i extracted from output variable V^k. Therefore, for identifying parameter X_i from dynamic behavior of generator, output variables with higher corresponding DI index are the most informative. In other words, parameters H and X'_d are estimated more effectively from the information concealed within variation of active and reactive power as output variables as opposed to other output variables.

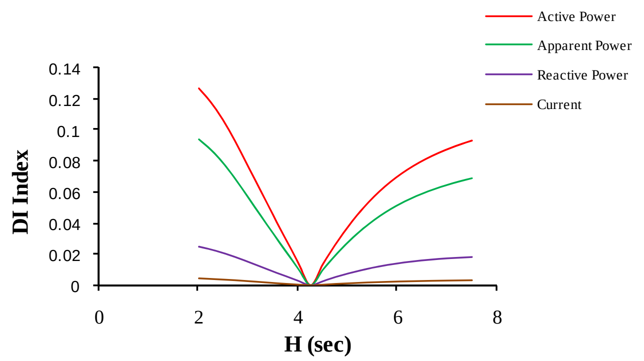

FIG. 6 VARIATION OF DI INDEX WITH RESPECT TO H WHEN FAULT IS LOCATED ON GENERATOR TERMINAL

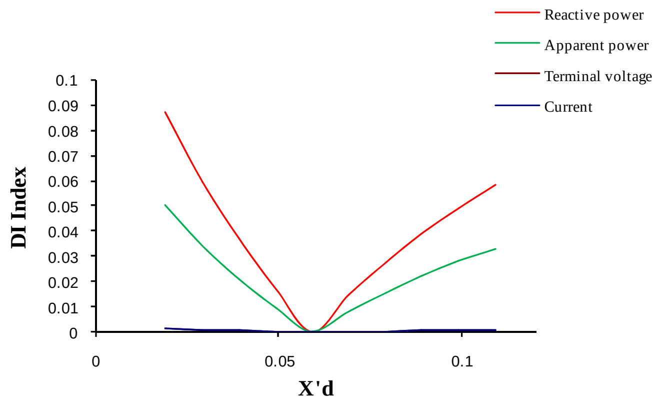

FIG. 7 VARIATION OF DI INDEX WITH RESPECT TO X'd WHEN FAULT IS A STEP CHANGE IN INPUT POWER OF TURBINE

TABLE 3 shows the priority of generator output variables in recognizing and identifying generator parameters when a three-phase short circuit is applied as a severe fault on the terminal of generator under study. It is obvious from this TABLE when a severe fault is applied on generator terminal for all parameters except X_q , the active, reactive and apparent power have been mostly affected by change in generator parameters. In other words, these outputs are the most informative variables for identification of generator parameters. For X_q the most affected output variable is rotor angle. TABLE 4 shows the priority of output variables of generator under study when the disturbance is a step change in turbine output power.

From this TABLE for all parameters except X_q, the reactive power variation has a dominant effect on identification of generator parameters and active power has the least effect on identification of parameters. From TABLEs 3 and 4, it can also be concluded that the output power variables are mostly affected by change in parameters of generator.

TABLE 3 PRIORITY OF OUTPUT VARIABLES FOR IDENTIFICATION OF GENERATOR PARAMETERS WHEN FAULT IS APPLIED ON GENERATOR TERMINAL

Parameter	Interval of variation From-to	Priority of output variables 1	2	3	4	5
X_d	0.144-0.444	Q	S	P	δ, I	
	0.444-1.044	Q	S	P	δ, I	
X'_d	0.019-0.059	Q	S	P	δ, I	
	0.059-0.109	Q	S	P	δ	I
X''_d	0.012-0.042	Q	S	P	δ	I
	0.042-0.182	Q	S	P	δ	I
X_q	0.117-0.417	δ	Q	S	P	I
	0.417-0.917	δ	Q	S	P	I
X'_q	0.01-0.08	P	S	Q	δ, I	
	0.08-0.18	P	S	Q	δ, I	
X''_q	0.19-0.39	P	S	Q	δ, I	
	0.39-0.186	P	S	Q	δ, I	
T'_d	0.184-0.984	Q	S	P	δ	I
	0.984-1.88	Q	S	P, δ	I	
T''_d	0.012-0.026	S, P	Q	δ	I	
	0.026-0.05	Q, S	P	δ	I	
T'_q	0.054-0.154	P	S	Q	δ, I	
	0.154-1.054	P	S	Q	δ	I
T''_q	0.13-0.25	P	S	Q	δ	I
	0.25-0.55	P	S	Q	δ, I	
H	2-4.25	P	S	Q	δ, I	
	4.25-7.5	P	S	Q	δ, I	

TABLE 4 PRIORITY OF OUTPUT VARIABLES FOR IDENTIFICATION OF GENERATOR PARAMETERS WHEN FAULT IS A STEP CHANGE IN OUTPUT POWER OF TURBINE

Parameter	Interval of variation From-to	Priority of output variables 1	2	3	4	5
X_d	0.144-0.444	Q	S	δ	I, V	
	0.444-1.044	Q	S	δ	I, V	
X'_d	0.019-0.059	Q	S	δ	I, V	
	0.059-0.109	Q	S	δ	I, V	
X''_d	0.012-0.042	Q	S	δ	I	V
	0.042-0.182	Q	S	δ	I	
X_q	0.117-0.417	δ	Q	S	I	
	0.417-0.917	δ	Q	S	I	
X'_q	0.01-0.08	Q	S	δ	I	V
	0.08-0.18	Q	S	δ	I, V	
X''_q	0.19-0.39	Q	S	δ	I, V	
	0.39-0.186	Q	S	δ	I	V
T'_d	0.184-0.984	Q	S	δ	I, V	
	0.984-1.88	Q	S	δ	I, V	
T''_d	0.012-0.026	Q	S	δ	I	V
	0.026-0.05	Q	S	δ	I	V
T'_q	0.054-0.154	Q	S	δ	I	V
	0.154-1.054	Q	S	δ	I, V	
T''_q	0.13-0.25	Q	S	δ	I, V	
	0.25-0.55	Q	S	δ	I, V	
H	2-4.25	Q	S	δ, I	V	
	4.25-7.5	Q	S	δ, I	V	

Conclusions

In this paper, estimation of generator parameters from its dynamic behavior has been investigated. For this purpose, changeability of generator dynamic behavior with respect to change in its parameters is adopted as criteria for measuring estimation of parameters within dynamic behavior. The variation of output variables "active, reactive, apparent powers, terminal voltage, armature current and rotor angle", are chosen as representative for dynamic behavior of generator. The deviation of generator outputs with respect to change in parameters is defined as deviation index DI which indicates the estimation of each parameter within variation each output variable. 11 parameters and 6 output variables of generator are chosen and simulation studies have been carried out employing two kinds of disturbances including a three-phase short circuit at the generator terminal and a step change in turbine output power. Deviation Index DI of output variables with respect to a specific parameter is considered to identify the priority of output variables of generator including active, reactive and apparent power, terminal voltage, armature current and rotor angle of generator for identifying that parameter. In all cases, simulation results show that the most proper output variables for identifying the generators parameters are the variables of the type of power in terms of reactive and active power.

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